Investigation on the contact hardening of Al/Steel laminated composites with soft interlayers

LEONID GUREVICH*, YURIY TRYKOV, DMITRY PRONICHEV and MIKHAIL TRUNOV
Volgograd State Technical University
Materials Science chair
Lenin avenue, 28, 400005, Volgograd
RUSSIAN FEDERATION
*Corresponding email: mv@vstu.ru

Abstract: The study presents results of finite element simulations and experimental investigations of tensile tests of the laminated metal Al alloy/steel composite with soft aluminum interlayer. The results were obtained for the range of interlayer thicknesses and different interlayer strength values. The relative interlayer thickness value corresponding to the rupture of the aluminum alloy was identified.

Key–Words: Laminated composites, steel, aluminum, soft interlayer, explosion welding

1 Introduction

Laminated Al/steel composites combine high values of typical for steel properties of hardness, durability and high-temperature strength with high thermal conductivity of Al alloys.

The key applications of Al/steel bimetals are found in shipbuilding as joints between steel hull and Al superstructures [1], Al tanks in chemical industry are lined with stainless steels, Al/steel composites are widely used in nuclear engineering as transition parts in pipeline equipment and in rocket construction to join Al cuff with stainless steel rings in Al pipelines.

The formation of brittle Fe_xAl_y phases and high thermal stresses in the adjacent to the bond zones are caused mainly by significant differences in chemical properties, linear expansion coefficients, melting points, heat conductivity and capacity of the base plates of the composite [2].

The bonds between steel and medium or high-strength Al alloys obtained by any existing technology possess high value of strength, but low values of durability, lack of stability of mechanical properties and break after treating above $400\,^{\circ}\mathrm{C}$. In order to avoid the disadvantages of such bonds Al alloy/steel composites are manufactured with thin aluminum interlayers that define the strength of the composite [3].

Under perpendicular to the bond plane tensile loads the mechanical properties of the composite depend on the relative thickness of the interlayer $\chi = \delta/d$, where δ is the thickness of the Al interlayer, d - transverse dimension of the test sample [4]. Bakshi, Gurev, Tron et al. proposed equations to assess strength properties of fuse and pressure contact steel welds [5, 6, 7]. Based on the equations the authors in [8] developed the classification of the joints with different types of mechanical heterogeneity and proposed semi-empirical methods to calculate the strength of the joints.

To choose the right treatment in order to obtain high-strength Al alloy/Al/steel bonds the contact hardening [4] of Al interlayer should be considered using, for example, FEM simulation for the range of relative thicknesses $\chi = \delta/d \leq 0,9$.

Explosion welded Al-6Mg/AA1135/S32109 composite is highly mechanically heterogeneous both after explosion bonding and subsequent heat treatments. To obtain the strength value and characteristics of deformation of the composite, depending on the relative thickness of the interlayer and do FEM simulations of the deformation we used relations proposed in [5].

The model of the composite to calculate its strength was defined as: H(Hard)-S(Soft)-MH(more Hard). The properties of the materials satisfied the expression: $\sigma_b^H \geq \sigma_y^{MH}$, where σ_b^H is the tensile strength of Al-6Mg, σ_y^{MH} - yield strength of steel. The mechanical heterogeneity coefficient was calculated by:

$$K_B = \frac{\sigma_b^H + \sigma_b^{MH}}{2\sigma_b^S} \leq 3, \tag{1}$$

where σ_b^S tensile strength of the soft interlayer.

As proposed by the model if $\chi > \chi_0$, (fig. 1, a), the strength of the bond is equal to the ultimate strength of the soft interlayer σ_b^S, while if $\chi < \chi_0$ the contact hardening effect is observed. During the effect the shear stress occurs on contact boundaries and leads to the 3-dimensional stress state. In case of perfect elasticity the hardening of the interlayer can be calculated using:

$$\sigma_b = \sigma_b^S \cdot K_\chi, \tag{2}$$

where $K_\chi = \frac{\pi}{4} + \frac{1}{3\cdot\sqrt{3}\chi}$ denotes the contact hardening coefficient.

When χ reaches the critical point, the effect of contact hardening is not fully observed for the interlayer due to other layers begin to plastically deform. The degree of mechanical heterogeneity, which is mathematically considered by K_B and the interlayer dimensions have a significant role in the involvement of hard materials into plastic deformation. "The softening effect" can result in the plastic deformation of the adjacent to the interlayer hard metal at the values of stress lower than tensile strength of hard metal σ_y^H. To consider this effect the authors of [8] introduced the concept of the realization of contact hardening coefficient K_h and its analytical equation: $K_B = \frac{\sigma_b^H}{\sigma_b^S} \leq 2.1$. Thus

$$\sigma_b = \sigma_b^S \times K_\chi \times K_H, \tag{3}$$

where $K_h = 1.25 - 0.25 \cdot K_B$

However such an approach can be applied only to simple shape constructions without considering load speed and surrounding temperature, while the materials of the composite should have close values of elastic modulus. FEM software allows predicting the behavior of the composite under elaborate conditions. This study aims to verify the FEM model of the laminated metal Al-6Mg/AA1135/S32109 composite under tensile load at room temperature.

2 Mechanical tests and computer modeling

To verify the FEM simulation results the 3-layerd Al-6Mg/AA1135/S32109 plate was obtained via explosion welding (EW). Chemical composition of the layers is presented in table 1.

The thickness of the plate was approximately 33 mm, while the thickness of the Al interlayer was in the range between 0.24 and 3 mm. The EW parameters were chosen to obtain the composite with the strength value of hardened AA1135 interlayer (AA1135 was hardened during EW and contact hardened during tensile load). Heat treatment of the composite at $350\,^\circ$C for 1 hour reduced the effect of hardening after EW in the interlayer. The tensile samples were cut from the three-layered EW and heat-treated plate. During the tensile tests the tensile load was applied transversely to the bond planes.

FEM simulation of the three layered composite tensile tests was carried out using ABAQUS software. The calculated Misses stress was compared to the ultimate stress of the materials. The plasticity of the material was considered using Jonson-Cook model [9], according to which the yield strength is calculated by:

$$\sigma_Y = \left(A + B \cdot \epsilon_p^n\right) \times \left(1 + C \cdot \ln \frac{\dot{\epsilon}_p^n}{\dot{\epsilon}_0}\right) \times \\ \times \left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right], \tag{4}$$

where ϵ_p - accumulated plastic strain, $\dot{\epsilon}_p$ - plastic strain rate, $\dot{\epsilon}_0$ - reference strain rate, T current temperature, T_r - room temperature, T_m - melting temperature, A, B, C, n and m - model constants. Equation (4) represents the hardening function of the material.

The Jonson-Cook model is usually observed without considering the effects related to the speed of loading and surrounding temperature. To describe the rupture of the material the Jonson-Cook model [10] considers the finite element breaking when parameter D is equal to 1:

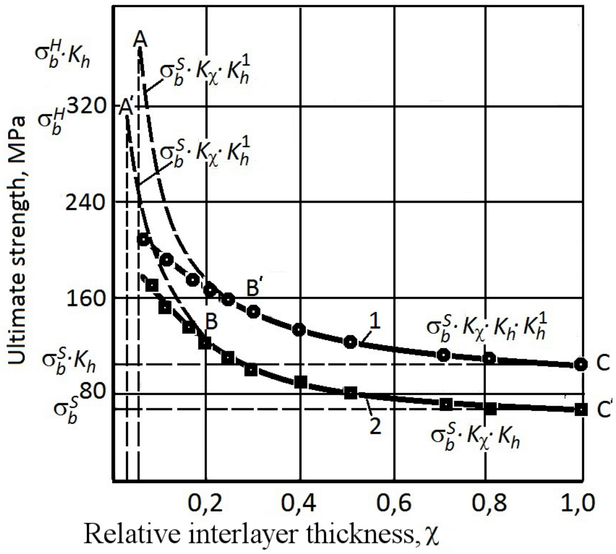
$$D = \frac{1}{\epsilon_f} \sum_i \Delta\epsilon_p^i, \tag{5}$$

where $\Delta\epsilon_p^i$ – the increment of equivalent plastic strain which occurs during an integration cycle, ϵ_f the equivalent strain to fracture:

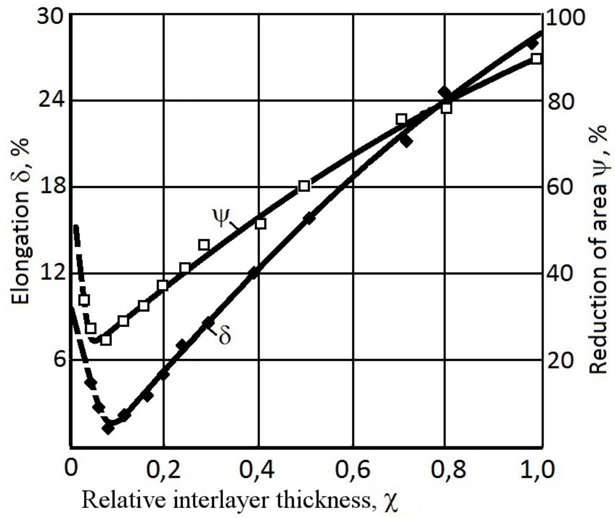
$$\epsilon_f = \left[D_1 + D_2 \exp\left(D_3 \cdot \frac{p}{\sigma_{ef}}\right)\right] \times \\ \times \left(1 + D_4 \ln\left[\frac{\epsilon_p}{\epsilon_0}\right]\right) \times \left(1 + D_5 \frac{T - T_r}{T_m - T_r}\right) \tag{6}$$

The numeric values of the parameters used in this study were observed in [11, 12, 13, 14] and are presented in tables 2 and 3. The effect of the speed of deformation was not considered due to the low value of $\dot{\epsilon}_p$. The Jonson-Cook model parameters were not set for steel, because the rupture of this component is impossible. In order to take into account the condition of Al-6Mg after EW and after heat treatment the coefficients of Jonson-Cook model were considered for two cases: Al-6MgH112 and Al-6Mg-O [15]:

In order to save computation time axisymmetric models were observed in our study. The interlayer thickness was in the range from 0.1 mm ($\chi = 0.033$) to 4 mm ($\chi = 0.66$), the thickness of steel and Al alloy plates was 10 mm. Interlaminar bond strength was equal to the strength of the weakest element of the composite. The load speed was 0.02 mm/sec.



(a)



(b)

Figure 1: The influence of the soft interlayer relative thickness on (a) ultimate strength and (b) plasticity of the Al-6Mg/AA1135/S32109 composite: 1) After EW 2) After heat treatment at 350 °C for 1 hr, K_1^h – coefficient considering the hardening of the soft interlayer

Table 1: Chemical composition of the materials used in this study

Material	Chemical composition, wt. %							
Al-6Mg	Mg, 6	Fe, 0.4	Mn, 0.6	Cu, 0.1	Zn, 0.2	Ti, 0.06	Be, 0.002	Al, 91.1-93
AA1135	Fe, 0.3	Mn, 0.025	Ti, 0.15	Cu, 0.05	Mg, 0.05	Zn, 0.1	Al, >99.3	
S32109	C, <0.12	Mn, <2	Ni, 9-11	S, <0.02	P, <0.035	Cr, 17-19	Cu, 0.3	Fe, 67

3 Results and discussion

The results of tensile tests have revealed that the reduction of the relative thickness of the interlayer in the range $0,65 \geq \chi \geq 0,08$ causes the increase of the ultimate strength of the EW composite from 100 MPa to 210 MPa; recrystallization annealing at $350 - 400$ °C for 1 hour reduced the explosion welding hardening of the interlayer and Al-6Mg, as a result in the range $1,0 \geq \chi \geq 0,65$ the ultimate strength value dropped to the level of AA1135 interlayer; the reduction of χ to 0.08 increased the strength value of heat treated specimen up to 175 MPa.

The comparison between experimental and calculated via (2) and (3) results revealed the required convergence in the range where $\chi > 0,28$ for the EW specimens and in the range where $\chi > 0,18$ for the heat treated specimens (fig. 1). Smaller values of χ contribute to the insufficient implementation of contact hardening of the AA1135 interlayer due to plastic deformation of the Al-6Mg plate in zones adjacent to the interlayer which result in the experimentally obtained curve points being under the calculated curves AB and AB. Taking into consideration the values of the contact hardening coefficient, contact hardening realization coefficient and the explosion hardening coefficient the new approximate position of the curve was obtained via graphical method, according to which the strength value for Al-6Mg/AA1135/S32109 laminated composite and Al-6Mg alloy are equal at values of $\chi < 0.02$, which corresponds to the interlayer thickness of 0.12 mm in case if the diameter of the specimen is 6 mm.

Experimental investigation of plastic properties of the Al-6Mg/AA1135/S32109 composite at different values of the interlayer thickness (fig. 1 b) revealed the longitudinal residual strain to be localized mainly in the interlayer at $\chi > 0.02$. The elongation of the composite defined mainly by AA1135 is 30% after heat treatment at 350 °C for 1 hour. The reduction of χ to 0.08 caused the decrease in the elongation down to 4% (at the thickness of the interlayer of 0.48mm) and the implication of Al-6Mg plate zones adjacent to the interlayer into plastic deformation which can be explained by softening effect [5].

The results obtained using SIMULIA/ABAQUS

Table 2: Johnson Cook constitutive model parameters for materials used in this study

Material	Johnson Cook constitutive model parameters [8]							
	A, MPa	B, MPa	m	n	$\dot{\epsilon}_0$, s^{-1}	T_m, K	T_r, K	Source
Al-6Mg-H112	218,3	704,6	0,93	0,62	1	773	293	[13]
Al-6Mg-O	168,4	950,5	1,08	0,71	1	773	293	[14]
AA1135	60	6,4	0,859	0,62	1	933	293	[11]
S32109	238	1202,4	1,083	0,675	1	1673	293	[14]

Table 3: Fracture constants for materials used in this study

Material	Fracture constants [10]								
	D_1	D_2	D_3	D_4	D_5	$\dot{\epsilon}_0$, s^{-1}	T_m, K	T_r, K	Source
Al-6Mg	0,178	0,389	-2,246	0	0	1	873	293	[10]
AA1135	0,071	1,428	-1,142	0,0097	0	1	933	293	[11]

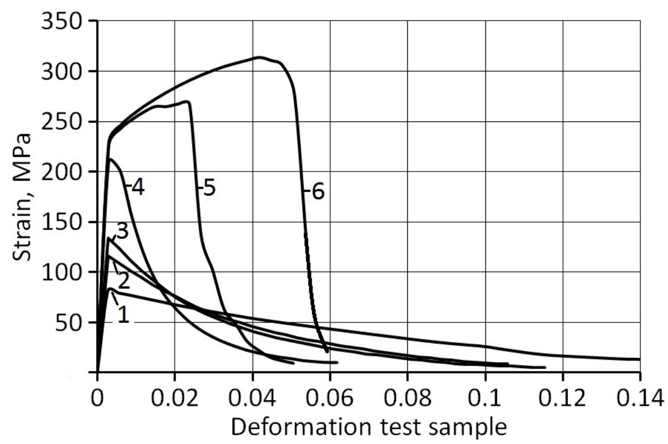
software revealed the relation between the deformation as well as the rupture character of the base plates of the composite and the relative interlayer thickness value (fig. 2).

According to the simulations the fracture was observed only in the AA1135 interlayer (for the composites with Al-6Mg-H112 or Al-6Mg-O) in the whole range of χ values used in this study. The decrease of χ value increased the tensile strength of the composite and the plastic deformations localized mainly in the interlayer (fig. 3). At $\chi \leq 0,033$ the deformation of the base Al-6Mg layer was observed (fig. 4). In case when the material of the base plate was Al-6Mg-H112 the strength of the composite improved, however the modification significantly decreased the maximum strain value on strain-stress curves.

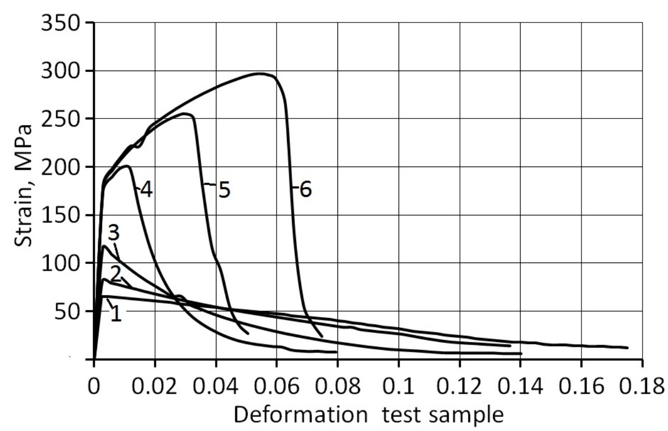
Experimentally obtained values of tensile strength of the heat treated at $350-400\,^{\circ}\mathrm{C}$ for 1 hour Al-6Mg/AA1135/S32109 composite (fig. 1) converge with the results of FEM simulation of tensile tests for Al-6Mg-H112/AA1135/S32109 and Al-6Mg-O/AA1135/S32109 composites in the observed range of χ (fig. 4). The difference between ultimate strength values for Al-6Mg-H112/AA1135/S32109 and Al-6Mg-O/AA1135/S32109 composites increase with the reduction of relative thickness value, but even when $\chi = 0,0166$ the difference is less than 5.7%.

During FEM simulation it was observed for composites with Al-6Mg-H112 or Al-6Mg-O that at $\chi > 0,0166$ the plastic deformation is mainly localized in the interlayer and in case when the thickness of interlayer is 0.1 mm the base Al-6Mg plate also begins to plastically deform (fig. 5).

In order to obtain the three-layered Al-6Mg/AA1135/S32109 composite with high value of strength and the required plasticity the parameters



(a)



(b)

Figure 3: Stress-strain curves for the specimen with 10 mm layer thicknesses of Al-6Mg and S32109: a) - Al-6Mg-H112, b) - Al-6Mg-O; 1 - $\chi = 0,667$; 2 - 0,333; 3 - 0,167; 4 - 0,0667; 5 - 0,0333; 6 - 0,0167

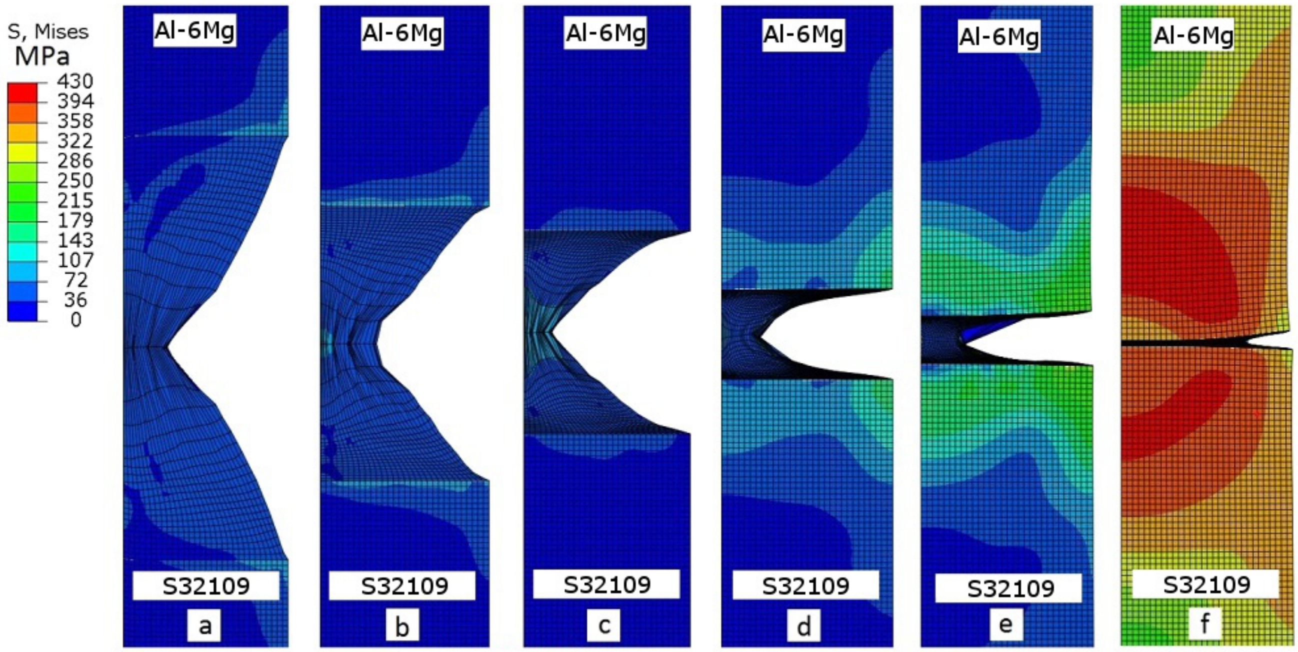
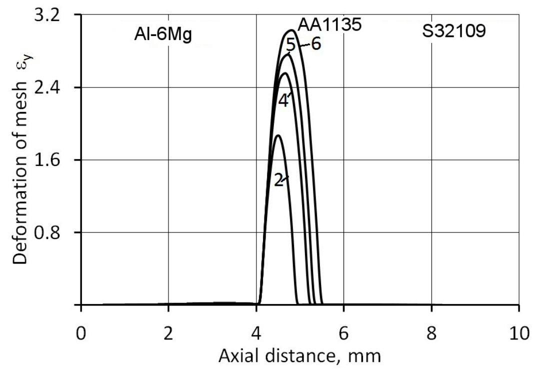
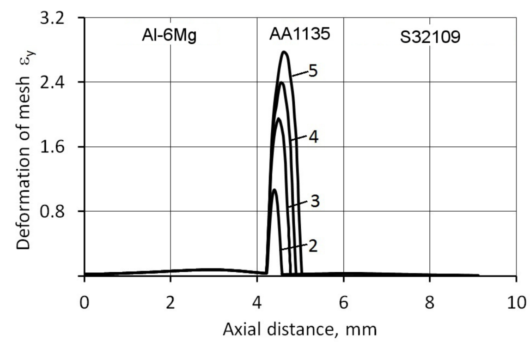


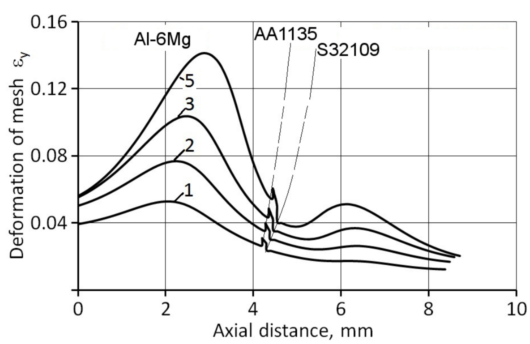
Figure 2: Von Mises stress distribution in Al-6Mg-H112/AA1135/S32109 composite before rupture: a) $\chi = 0,667$; b) - 0,333; c) - 0,167; d) - 0,0667; e) - 0,0333; f) - 0,0167



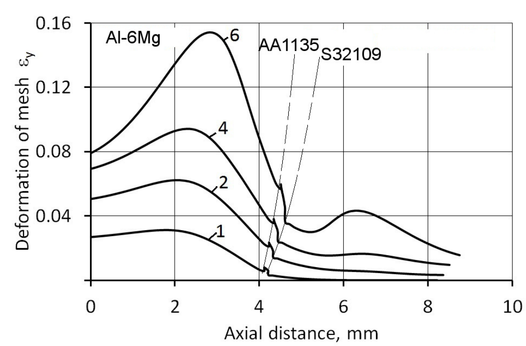
(a)



(b)



(c)



(d)

Figure 5: Strain value distribution in the interlayer and adjacent to the interlayer zones in Al-6Mg and S32109: a-c composite, containing Al-6Mg-H112, d - composite, containing Al-6Mg-O, a - $\chi = 0,0667$; b - $\chi = 0,0333$; c and d - $\chi = 0,0166$; 1 - specimen deformation 0.3 mm; 2 - 0,6 mm; 3 - 0,78 mm; 4 - 0,9 mm; 5 - 1,02 mm; 6 - 1,2 mm

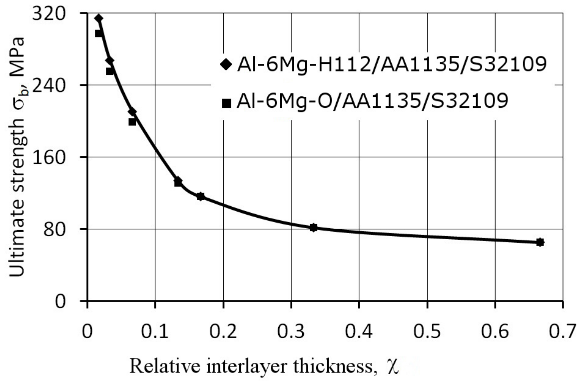


Figure 4: The relation between obtained during simulation Al-6Mg/AA1135/S32109 ultimate strength value and relative thickness of the interlayer

of the soft interlayer should be carefully chosen. However the manufacture of such composites is extremely difficult due to low value of required interlayer thickness.

4 Conclusion

- In this study we verified the results of the modeling via Abaqus/Simulia software of the 3-layered composite behavior under tensile tests in the range of relative interlayer thickness values.
- Using experimental and FEM approaches it was found that the decrease in the relative interlayer thickness value leads to the increase of the tensile strength value of the composite. The plastic deformation under the tensile tests is localized mainly in the soft interlayer. The deformation of Al-6Mg layer was identified only in the range where $\chi \leq 0,033$

5 Acknowledgements

The present study was supported by Russian Scientific Fund via project 14-19-00418

References:

[1] Long Li, Fu Xing Yin, and Kotobu Nagai. "Progress of laminated materials and clad steels production". In: *Materials Science Forum*. Vol. 675. Trans Tech Publ. 2011, pp. 439–447.

[2] Leonardo Agudo et al. "Intermetallic Fe x Al y-phases in a steel/Al-alloy fusion weld". *Journal of materials science* 42.12 (2007), pp. 4205–4214.

[3] Weihua Zhang et al. "Interfacial microstructure and mechanical property of resistance spot welded joint of high strength steel and aluminium alloy with 4047 AlSi12 interlayer". *Materials & Design* 57 (2014), pp. 186–194.

[4] K Satoh and M Toyada. "Joint Strength of Heavy Plates With Lower Strength Weld Metals". *Welding journal* 54.9 (1975), p. 311.

[5] O.A. Bakshi, N.K. Zaitsev, and K.M. Gumerov. "Crack resistance of interlayers in joints of different moduli subjected to static tensile loading". *Strength of Materials* 15.4 (1983), pp. 507–512.

[6] A.V. Gur'ev et al. "Calculated static tensile strength of composite specimens with soft interlayers". *Strength of Materials* 5.1 (1973), pp. 7–11.

[7] A.S. Tron' et al. "Strength of thin metal interlayers in composites". *Strength of Materials* 7.5 (1975), pp. 573–576.

[8] Yu.P. Trykov, L.M. Gurevich, and V.G. Shmorgun. *Sloistyye kompozity na osnove alyuminiya i yego splavov*. Metallurgizdat M., 2004.

[9] Gordon R Johnson and William H Cook. "A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures". In: *Proceedings of the 7th International Symposium on Ballistics*. Vol. 21. The Netherlands. 1983, pp. 541–547.

[10] Gordon R Johnson and William H Cook. "Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures". *Engineering fracture mechanics* 21.1 (1985), pp. 31–48.

[11] V.A. Kuz'kin and D.S. Mikhalyuk. "Primeneniye chislennogo modelirovaniya dlya identifikatsii parametrov modeli Dzhonsona-Kuka pri vysokoskorostnom deformirovanii alyuminiya". *Computational continuum mechanics* 3.1 (2010), pp. 32–43.

[12] A.V. Tret'yakov and V.I. Zyuzin. "Mekhanicheskiye svoystva metallov i splavov pri obrabotke davleniyem. M". *Metallurgiya* 4 (1973).

[13] Wei Zhang et al. "Dynamic mechanical behavior and microstructural evolution of the Al-6Mg alloy subjected to three treatment conditions". *Journal of Wuhan University of Technology-Mater. Sci. Ed.* 27.3 (2012), pp. 432–436.

[14] EA Flores-Johnson et al. "Numerical analysis of the effect of weld-induced residual stress and plastic damage on the ballistic performance of welded steel plate". *Computational Materials Science* 58 (2012), pp. 131–139.

[15] J Gilbert Kaufman. *Introduction to aluminum alloys and tempers*. ASM International, 2000.